

DESIGN OF ROCK CHUTES

by

K. M. Robinson, P.E., C. E. Rice, P.E. and K. C. Kadavy, P.E.
Research Hydraulic Engineers and Agricultural Engineer
USDA, Agricultural Research Service
Stillwater, Oklahoma

Written for presentation at the
1997 ASAE Annual International Meeting
Sponsored by ASAE

Minneapolis Convention Center
Minneapolis, Minnesota
August 10-14, 1997

Summary:

Rock chute design information is brought together from several sources to provide a more comprehensive design tool. The slope stability, boundary roughness, and outlet stability of rock chutes are discussed as are numerous related design topics. This paper contains most of the information needed to complete a rock chute design. Angular riprap with median stone sizes of 15 to 278 mm were tested on slopes ranging from 2.5 to 40%.

Keywords:

Riprap, Hydraulic Structures, Design, Chutes, Rock

The author(s) is solely responsible for the content of this technical presentation. The technical presentation does not necessarily reflect the official position of ASAE, and its printing and distribution does not constitute an endorsement of views which may be expressed.

Technical presentations are not subject to the formal peer review process by ASAE editorial committees; therefore, they are not to be presented as refereed publications.

Quotation from this work should state that it is from a presentation made by (name of author) at the (listed) ASAE meeting.

EXAMPLE — From Author's Last Name, Initials. "Title of Presentation." Presented at the Date and Title of meeting, Paper No. X. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659 USA.

For information about securing permission to reprint or reproduce a technical presentation, please address inquiries to ASAE.

Design of Rock Chutes

by

Kerry M. Robinson, P.E.¹, Charles E. Rice, P.E.¹ and Kem C. Kadavy, P.E.²

Abstract

Rock chute design information is brought together from several sources to provide a more comprehensive design tool. The slope stability, boundary roughness, and outlet stability of rock chutes are discussed, as are numerous related design topics. This paper contains most of the information needed to complete a rock chute design. Angular riprap with median stone sizes of 15 to 278 mm were tested on slopes ranging from 2.5 to 40%.

Introduction

Rock chutes or loose-riprap-lined channels are used to safely conduct water to a lower elevation. These structures provide an alternative method of protecting the soil surface to maintain a stable slope and to dissipate some flow energy. Watershed management applications for this type of structure are numerous for uses such as channel stabilization, grade control, and embankment overtopping. Depending on the availability and quality of accessible rock materials, rock chutes may offer economic advantages over more traditional structures. Flow cascading down a rock chute is visually pleasing, and these structures offer aesthetic advantages for sensitive locations. Construction of these chutes can be performed with unskilled labor and a comparatively small amount of equipment. A typical rock chute profile is shown as figure 1.

These structures, typically constructed on slopes of 10 to 40%, have been the subject of several recent investigations. The objective of this paper is to bring together pertinent information from several sources to provide the designer with a more comprehensive design tool.

Related Work

Rock chutes in various forms have been used for many years, so this design concept is not new. Isbash (1936) examined the ability of flowing water to move rocks. The shape of a rock fill cross-section was described while stone of a known size and weight was deposited in running water. Isbash developed a relationship describing the minimum velocity necessary to move stones of a known size and specific gravity. Anderson et al. (1970) developed a design procedure for riprap-lined drainage channels by testing rounded stone on relatively flat slopes. Uniformly sized riprap

Contribution of the United States Department of Agriculture, Agricultural Research Service in cooperation with the Oklahoma Agricultural Experiment station. ¹Research Hydraulic Engineers and ²Agricultural Engineer, Hydraulic Engineering Research Unit, Plant Science and Water Conservation Research Laboratory, Agricultural Research Service, 1301 N. Western St., Stillwater, OK 74075.

materials remained stable at higher flow rates than non-uniform materials. The non-uniform materials did a better job of protecting the filter material below the rock layer. Whittler and Abt (1990) found that the stone gradation has a significant influence on chute performance. The uniformly sized riprap withstood higher flow rates than non-uniform material of the same D_{50} . The uniform material did fail more suddenly than the non-uniform materials once the slope became unstable.

Abt et al. (1987) and Abt and Johnson (1991) tested both angular and rounded stone and found that the rounded stone failed at lower unit discharges than the same stone size with an angular shape. These researchers developed design criteria for median stone sizes between 25 and 152 mm on slopes ranging between 1 and 20%. Maynard (1988) developed a riprap sizing method for stable open channel flows on slopes of 2% or less. This design method, based on the average local velocity and flow depth, used the D_{30} as the characteristic rock size. The effects of riprap gradation, thickness, and shape were also examined. Maynard (1992) extended this design method to slopes between 2 and 20% for nonimpinging flows. Frizell and Ruff (1995) examined riprap with a D_{50} of 380 mm on 2:1 slopes (horizontal : vertical). These researchers investigated riprap for embankment overtopping protection.

Anderson et al. (1970) developed a relationship for the boundary roughness of rock-lined channels. The Manning roughness was described as a function of the stone size only. Abt et al. (1987) also developed a relationship that predicts the Manning roughness as a function of the bed slope and stone size.

Rock chutes testing performed at the USDA-ARS Hydraulics Engineering Unit is the primary source of information for this report. These tests focused on three specific areas: slope stability, roughness, and outlet stability. Robinson et al. (1995) reported an empirical slope stability relationship for rock sizes ranging from 15 to 145 mm on slopes of 10 to 40%. This stability relationship predicts rock size as a function of the discharge and channel slope. Robinson et al. (1997) revised this design relationship in an attempt to better represent the data base. Rock chutes were tested to failure in three different flumes as well as full-size prototype structures for slopes of 8-40% and median rock sizes up to 278 mm. Rice et al. (1996) examined six design procedures and compared their results for a range of discharges and bed slopes. Rice et al. (1997) developed empirical relationships to predict the Manning roughness coefficient as a function of stone size and bed slope. These roughness relationships allow calculation of the flow depth in a rock chute. Tests were also conducted (C.E. Rice, 1997, personal communication) to examine the rock size necessary to maintain stability of the rock chute outlet. Much of this work will be summarized herein.

Riprap Properties

The rock chutes testing described in this paper was performed using predominantly angular crushed limestone with a D_{50} of 15 to 278 mm. The rock layers in all tests were $2D_{50}$ thick. The D_{50} is the particle size for which 50% of the material sample is finer. The median stone diameter and the D_{50} are considered equal. Rock used in this study displayed a coefficient of uniformity ($C_u = D_{60}/D_{10}$) of 1.25 to 1.73. The specific gravity of the stones ranged from 2.54 to 2.82. The geometric standard deviation ($\sigma_g = D_{84.1}/D_{50} = D_{50}/D_{15.9}$) ranged from 1.15 to 1.47, while the length to width

ratio (L/B) ranged from 1.98 to 2.36. The geometric stone properties were similar for all rock sizes, and the gradations exhibited by these materials were relatively uniform.

Sufficient quantities of each material were sampled to accurately represent each rock size. ASTM (1996) Standard D5519 suggests that a sample size should be large enough to ensure a representative gradation and to provide test results to the desired level of accuracy. The specimen size should be large enough that the addition or loss of the largest stone in the sample will not change the results by more than a specified amount. For this study the largest element in each test material represented 0.7% to 3.1% of the sample weight.

Results and Discussion

Slope Stability

Rock chute stability tests were performed in three separate flumes with widths of 0.76, 1.07, and 1.83 m (2.5, 3.5, and 6.0 ft). Two full size prototype structures were also constructed and tested to failure. These large-scale chutes were constructed with a 2.74-m (9-ft) bottom width and 2:1 side slopes. A total of 29 rock chute stability tests were performed on slopes ranging from 8 to 40% for median rock sizes of 15 to 278 mm (Robinson, et al., 1997). The tests were performed by introducing a base flow in the rock chute, then increasing the flow incrementally. Orifice plates and air-water differential manometers were used to measure flow in the two smaller models, while Parshall flumes were used to measure flow in the larger models. Slope stability was observed at each flow rate, with particular attention paid to stone movement on the slope. The flow rate was increased until the rock chute was judged to be unstable.

The rock chutes stability tests failed in a relatively consistent manner. Typically as the flow rate was increased, smaller stones were repositioned or removed from the slope. This initial stone movement was generally observed at flow rates well below the design discharge. As the flow rate increased, additional stone movement occurred. Even though a small amount of material was being repositioned and/or removed, the entire chute remained stable. As the flow rate reached the highest stable discharge, larger stones were observed to vibrate, move on the slope, and/or tilt up into the flow. At higher discharges numerous larger stones would tilt into the flow and be transported downslope. These stones often caused a chain reaction by dislodging additional material. Channelization and/or scour holes were then observed in the rock layer, and the chute was considered to have failed.

Failure was defined as the flow condition that exposed the underlying geofabric or bedding material. As the slope decreases, however, the chute surface can become quite ragged without exposing the geofabric. Therefore, some subjectivity was involved in the determination of a highest stable discharge. The same procedures were followed in each test to minimize this subjectivity. The variability associated with the highest stable discharge determination is expected to increase as the chute slope decreases. The rock chute surface typically experienced the greatest damage just downstream of the crest on the sloping section. Test configurations used a $40D_{50}$ radius to improve the flow transition between the horizontal approach section and the sloping chute (Fig. 1). While this radius provides improved flow conditions for the

larger slopes, the influence of this radius diminishes as the slope decreases. While flow in these chutes tends to transition to normal depth relatively rapidly, the area most subject to failure is the upper reach of the chute just below the crest.

Rock chutes become more stable as the stone size increases and/or the slope decreases. A plot of the highest stable unit discharge (q) in $\text{m}^3/\text{s}/\text{m}$ versus the product of the median stone size (D_{50}) and the bed slope (S_o) in decimal form provides a convenient means of data separation (Fig. 2). A prediction equation was developed from 24 of the 29 stability tests as follows:

$$q = (D_{50} S_o)^{1.40+0.213/S_o^{0.5}} \exp(-11.2+1.46/S_o^{0.5}) \quad (1)$$

where: q = highest stable unit discharge, $\text{m}^3/\text{s}/\text{m}$
 D_{50} = particle size for which 50% of the sample is finer, mm
 S_o = decimal slope, dimensionless

This empirical function, shown graphically in figure 2, envelopes the data to always provide a conservative prediction. Equation 1 provides a reasonable representation of the performance of tests 1 through 24. Tests 25 through 29 were used as verification tests, and these test results are shown with a filled symbol in figure 2. The five verification runs, which include the two field-scale tests and three tests performed in the 1.83-m wide flume, represent the largest rock sizes examined in this study.

The five verification tests are also adequately represented by the prediction equation. The single test performed with an 8% bed slope was the only data point not conservatively predicted by equation 1. The highest stable discharge determination was more difficult as the rock chute slope decreased; therefore, the variability associated with the lower slope data is expected to increase. Sufficient data is not presently available to predict chute stability at slopes less than 10%, therefore equation 1 should be applied for bed slopes between 10 and 40%. Appropriate engineering judgment and an appropriate safety factor should be applied when using this equation. Caution should be exercised if this equation is applied outside the data base from which it was developed and verified.

Boundary Roughness

An estimate of the boundary roughness is necessary to effectively design a rock chute. The Manning equation is the most commonly used equation for expressing flow resistance in open channels.

$$n = (R^{2/3} S^{1/2}) / V \quad (2)$$

where: n = Manning roughness coefficient
 R = hydraulic radius, m
 V = average flow velocity, m/s
 S = energy gradient

Rice et al. (1997) developed an empirical relationship to predict the Manning roughness coefficient as a function of the median stone size (D_{50}) and the bed slope (S_o). The Darcy-Weisbach friction factor was also predicted as a function of the relative submergence (d/D_{84}). Tests were conducted in a 1.07-m wide flume and two 2.74-m wide field-scale structures using angular riprap with median diameters ranging from 52 to 278 mm. The bed slopes examined ranged from 2.5 to 33.3%.

Bed elevations were obtained along the channel centerline for each test condition. Discharge and flow depths were measured at each incremental test flow. Due to the extreme turbulence and air entrainment at the flow surface, the water surface elevations could not be accurately measured. The depth of flow was measured with piezometers placed in the bedding material.

Flow resistance is a function of the flow depth above the effective top-of-riprap elevation. While there is no recommended procedure for determining the effective top-of-riprap elevation, an accurate value is necessary to determine the Manning roughness coefficient. An error in the flow depth translates into a much larger error in the Manning coefficient. For example, a 10% error in the flow depth translates into a 17% error in the n value. The effective top-of-riprap elevation was determined using the measured unit discharge through the riprap, measured flow depths, and the Stephenson (1979) empirical equation for velocity through rock material:

$$V_m = n_p (S_o g D / K')^{1/2} \quad (3)$$

where: V_m = velocity through rock, m/s
 n_p = porosity
 g = gravitational acceleration, 9.81 m/s²
 K' = a dimensionless friction factor
 D = representative rock diameter in m (use D_{50} in m)

Abt et al. (1987) presented values for n_p of 0.44-0.46 for angular riprap. The factor K' is defined by Stephenson (1979) as:

$$K' = K + 800/R_e \quad (4)$$

where: K = 4 for crushed rock
 R_e = Reynolds number, $dV/n_p\nu$
 d = flow depth above top-of-riprap elevation
 ν = kinematic viscosity

The values of $800/R_e$ were small (<0.01); therefore, it was assumed that $K' = K = 4$. Using the measured flow depths at different percentage water coverage of the riprap, equation 3 was used to calculate the velocity through the rock materials. The calculated unit discharge through the riprap or mantle flow (q_m) was compared with the measured discharge. The maximum flow depth with good agreement between

calculated q_m and measured q_m occurred at about 95% coverage of the riprap. The effective top-of-riprap elevation was selected as the flow depth for which 95% of the riprap was covered. A plot of the bed surface elevation versus the horizontal station (Fig. 3) illustrates that the effective top-of-riprap falls between the maximum top-of-riprap elevation and the least squares fit of the measured elevation.

The Manning n was calculated using the surface discharge and average depths measured in the middle third of the slope length. The stable discharges near failure of the riprap were used in the analysis, since these discharges should result in the highest flow resistance. With $R = d$, $V = q_s/d$, and $S = S_o$, equation 2 can be used to calculate n . With these substitutions equation 2 becomes:

$$n = d^{5/3} S_o^{1/2} / q_s \quad (5)$$

where: d = flow depth above the effective top-of-riprap.
 q_s = surface unit discharge, ($q_t - q_m$)
 q_t = total unit discharge
 q_m = unit discharge through the riprap

The data of Rice et al. (1997) and Abt et al. (1987) both show a strong tendency for n to increase as the channel slope increases. Rice et al. (1997) combined the two data bases and developed the following roughness relationship:

$$n = 0.0292 (D_{50} S_o)^{0.147} \quad (6)$$

This relationship was developed for angular riprap on slopes between 10 and 40%. Rice et al. (1997) also expressed the combined data bases in terms of relative roughness $(8/f)^{1/2}$ and relative submergence (d/D_{84}) :

$$(8/f)^{1/2} = 5.1 \log(d/D_{84}) + 6 \quad (7)$$

This equation should give reasonable estimates of the Darcy-Weisbach friction coefficient (f) for loose, angular riprap on steep slopes.

Outlet Stability

The riprap size required for outlet stability was also examined in two separate flumes and two field-scale structures (C.E. Rice, 1997, personal communication). Angular riprap with a D_{50} ranging from 52 to 278 mm was tested at slopes ranging from 8 to 40%. For a given discharge, rock size, and slope the movement of riprap in the outlet section was observed for a range of tailwaters. An overflow tailgate was used to adjust the tailwater elevation in the 1.83- and 1.07-m wide flumes. An assumption was made that the worst case condition for outlet stability would occur at the maximum stable unit discharge predicted by equation 1 for a given riprap size and bed slope.

The tailwater elevation could be controlled with the flume tests but not with the field-scale structures. The field-scale structures were evaluated at the stable discharge and at two lesser discharges. The flumes tests were performed at tailwater (T_w) to median stone size (D_{50}) ratios of 3.0, 2.0, and the minimum resulting from the horizontal riprap section and downstream channel resistance.

The centerline bed surface profiles were measured before and after each test flow. The water surface profiles were measured on the chute and the outlet section. Air entrainment and turbulence made these measurements difficult at times. Typical water surface profiles in the outlet reach (Fig. 4) show that without a forced tailwater, the water surface stabilizes at a tailwater elevation slightly less than $2D_{50}$ due to the outlet reach and downstream channel resistance. While some minor shifting of the riprap along the slope was noted, no movement of the riprap was observed in the outlet reach. Notable movement of riprap in the outlet reach of the chute was not observed for any test. These tests provide evidence that the riprap size required for stability along the bed slope predicted by equation 1 will be stable for the outlet reach. Also, the results show that the minimum tailwater that occurs as a result of the outlet reach and downstream channel resistance is sufficient to ensure stability of the riprap in the outlet reach.

Observations were made during each test to establish the required length of horizontal riprap downstream of the sloping section. For most tests the primary attack on the riprap in the outlet reach extended to $12D_{50}$ downstream of the sloping section. In a limited number of tests, this attack continued to approximately $14D_{50}$ downstream. Therefore, a horizontal reach length of $15D_{50}$ or more is recommended downstream of the sloping chute (C.E. Rice, 1997, personal communication). The elevation of the top of riprap at the exit of the outlet reach should be at or below the downstream channel bed elevation to prevent unraveling or sloughing of the riprap. Unraveling of the riprap in the outlet reach could result in failure of the rock chute. The potential for bed degradation downstream of a chute should be considered when establishing the riprap elevation.

Related Design Topics

Numerous design considerations other than slope stability, roughness, and outlet stability can have a major influence on the performance of a rock chute. The discussion that follows is an attempt to identify a few of those potential problem areas and to briefly discuss their importance. In most cases, these related topics were not the main focus of this study, and traditional design techniques should be fully exploited to address these issues.

Seepage

Seepage problems should be carefully considered, since seepage and piping can threaten rock chute stability. Field-scale structures examined in this study used a nonwoven geofabric overlying a 50-mm thick layer of concrete sand. The sand helped to cushion the fabric during stone placement. A vertical cutoff was established by placing the fabric in a trench at the upstream and downstream limits of the chute. The fabric was also trenched in along the sides, and this precaution should be considered if

side inflow is a potential problem. The geofabric should be overlapped at joints to ensure the integrity of the barrier. The allowable stone drop height should also be limited to control impact damage to the geofabric. For some sites the treatment of seepage influences may be the most serious design issue. Since this study did not directly examine the influence of seepage on rock chute performance, designers should use all available design techniques to prevent piping and subsequent loss of foundation support.

Filters

Information is presently available concerning graded gravel filters. Also, numerous nonwoven geofabrics are available to help control movement of fines from the subgrade materials. This study examined $1D_{50}$ thick gravel filters placed on a geofabric and a geofabric placed on a 50-mm thick layer of concrete sand. Both methods appeared to work well, with no observed impact on chute stability. However, seepage and filter performance were not major points of this study. The designer should use appropriate techniques to prevent the subgrade material or the filter material from being drawn through the rock mantle by the flow. Anderson et al. (1970) observed that as the rock gradation became more uniform, the filter material could be more easily sapped through the rock mantle. The less uniform rock is thought to fill the interstitial space more fully and provide more protection to a graded filter.

Rock Gradation

Whittler and Abt (1990) and Anderson et al (1970) both conclude that uniformly sized riprap materials remained stable at higher flow rates than non-uniform materials, while the non-uniform materials did a better job of protecting the filter material below the rock layer. Whittler and Abt (1990) also found that uniform material failed more suddenly than the non-uniform materials once the rock chute became unstable.

Rock Sampling

The sample size should be large enough to ensure a representative gradation and to provide test results to the desired level of accuracy (ASTM, 1996). For this study, sample sizes were obtained such that the largest element in the sample represented no more than 3.1% of the sample weight. Mechanisms should be in place to ensure that a characteristic size or weight used in the design is actually delivered and placed in the rock chute.

Rock Quality

Design requirements dictate that a stone exhibit a specific size and gradation to achieve a desired performance. The rock durability is also important to ensure that the material remains intact throughout the design life of the structure. Susceptibility to freeze-thaw, abrasion, and chemical breakdown are important design considerations. The specific gravity of the rock material should meet or exceed design specifications.

Rock Shape

Stone shape has an influence on rock chute performance. Abt and Johnson (1991) found that rounded riprap fails at a unit discharge of approximately 40% less than angular riprap with the same median stone size. The rounded stones are also less likely to relodge on the slope once moved by the flow.

Side Slopes

The field-scale rock chutes examined in this study were constructed with 2:1 (horiz. : vertical) side slopes. For rock chutes with slopes between 10 and 40% the flow depths associated with design discharge are not large. Because the flow depths are relatively small, the side slope angle did not have a significant influence on chute stability. As the flow depth increases, the toe of the side slope would be expected to be a weak point. Caution is advised for side slopes steeper than 2:1.

Rock Placement

A rock chute should normally be constructed from the lowest elevation to the highest elevation. This practice lets the gravitational force of the stone's own weight hold the rock mantle together during placement, thereby minimizing voids in the rock layer. Care should be taken not to segregate or size classify the stone during placement. Allowing the stone to be pushed or rolled downslope is an example of stone segregation. Field-scale structures in this study were constructed with dumped-placed riprap. Some hand placement of stones was necessary to achieve a smooth chute surface. All rock chute tests were conducted with a $2D_{50}$ thick rock layer.

Flow Concentrations

Rock chutes should be constructed to minimize flow concentrations caused by surface irregularities. Approach conditions that allow flow concentrations should also be avoided if possible, since channel cross slopes or variations in bed slope can allow the flow to concentrate and increase the attack on the bed. A uniform, low velocity approach flow is the most desirable condition.

Geometric Considerations

Rock chutes examined in this study were constructed using a horizontal crest section, a sloping chute, and a horizontal exit reach. A radius of approximately $40D_{50}$ was used to transition between the horizontal crest and the sloping chute. This radius is particularly important since the chutes typically failed just downstream of the crest. The designer should insure that any flow disturbance is minimized at this location.

Hydrology

A rock chute is designed to safely operate up to a specific discharge. The anticipated runoff volume will vary if the watershed runoff parameters experience changes. If the rock chute is designed for a 10-year event, then a 50-year event should be expected to threaten or fail the structure.

Freeboard

Appropriate freeboard should be added to the design flow depth to ensure that the flow is contained in the channel. Some runup was observed along the side slopes during the three-dimensional tests. An estimate of the maximum runup to be expected can be made by calculating the velocity head using the average velocity. This velocity head value should be considered when applying a channel freeboard. The highly turbulent flow in a rock chute also creates splashing that tends to increase as the slope increases.

Factor of Safety

Appropriate engineering judgment should be applied when assigning a safety factor. Maynard (1992) suggests a minimum safety factor of 1.1. Equation 1 presented in this paper conservatively envelopes all data between 10 and 40%. Uncertainty concerning factors such as rock size and hydrology should be reflected in the safety factor. If damage cannot be tolerated, the safety factor should reflect that limitation as well.

Vandalism

Rock chutes have a relatively thin surface, and unauthorized removal or rearrangement of stones on this surface can have dire consequences. Cases have been observed where stone was removed for landscaping and other personal uses. Access control, inspections and maintenance activities should be in place to minimize vandalism and protect the structure.

Example Design

To reinforce the application of this design information, an example design is presented. In most cases the design discharge is known, and the bed width is varied to accept this flow. The bed slope can also be adjusted to obtain a desired stone size.

Given:

Energy slope (S) = Bed slope (S_o) = 0.20

Channel bottom width (B) = 5 m

Channel side slopes (Z) = 2:1

Total discharge (Q) = 3.0 m³/s

Find:

Required median stone size, D_{50}

Mannings roughness coefficient, n

Unit discharge through the rock mantle, q_m , and surface unit discharge, q_s

Flow depth, d

The design is applicable for angular crushed limestone placed in a $2D_{50}$ thick layer. The stone is placed directly on top of a nonwoven geofabric that overlays a 50-mm thick layer of concrete sand. The effective top-of-riprap is assumed to be $2D_{50}$ above the filter cloth. Equation 1 is used to determine the stone size required for slope stability.

The unit discharge (q) is $3.0 \text{ m}^3/\text{s}$ divided by the 5-m bed width ($q = 0.6 \text{ m}^3/\text{s}/\text{m}$). Since the channel is trapezoidal, the unit discharge will actually be slightly less. Rearranging equation 1 to solve for D_{50} yields the following expression:

$$D_{50} = \left[(q / \exp(-11.2 + 1.46/S^{0.5}))^{\frac{1}{1.40 + 0.213/S^{0.5}}} \right] / S \quad (8)$$

If $q = 0.60 \text{ m}^3/\text{s}/\text{m}$ and $S = 0.20$, then $D_{50} = 262 \text{ mm}$. Rearranging equation 5 to calculate the flow depth above the effective top-of-riprap (d) yields:

$$d = (n q_s / S_o^{0.5})^{3/5} \quad (9)$$

The Manning roughness coefficient can be determined from equation 6 :

$$n = 0.0292 (D_{50} S_o)^{0.147} \quad (6)$$

Substituting $D_{50} = 262 \text{ mm}$ and $S_o = 0.20$ yields $n = 0.052$. The surface flow unit discharge $q_s = (q_t - q_m)$. The total unit discharge (q_t) is $0.60 \text{ m}^3/\text{s}/\text{m}$, and the unit discharge through the mantle (q_m) = $V_m (2D_{50})$. The velocity through the rock mantle (V_m) is determined from equation 3:

$$V_m = n_p (S_o g D / K')^{1/2}$$

With $n_p = 0.45$, $S_o = 0.20$, $g = 9.81 \text{ m/s}^2$, $D = 0.262 \text{ m}$, and $K' = 4$, V_m is calculated to be 0.161 m/s . Therefore, $q_m = (0.161 \text{ m/s}) (2) (0.262 \text{ m}) = 0.084 \text{ m}^3/\text{s}/\text{m}$. Therefore, $q_s = 0.60 \text{ m}^3/\text{s}/\text{m} - 0.084 \text{ m}^3/\text{s}/\text{m} = 0.516 \text{ m}^3/\text{s}/\text{m}$.

Using equation 9 the flow depth (d) = 0.185 m .

Conclusions

Rock chutes were examined using three flumes and two field-scale structures. Angular limestone was tested in sizes ranging from 15 to 278 mm on slopes ranging from 2.5 to 40%. All tests were conducted using a horizontal approach, a sloping chute, and a horizontal escape reach. The rock layer was $2D_{50}$ thick for all tests. Tests were performed to better describe the slope stability, boundary roughness, and outlet stability of rock chutes. This paper brings together pertinent information from several sources to provide a more comprehensive design tool.

An empirical relationship is presented that describes the highest stable discharge as a function of the median stone size and bed slope. This enveloping relationship conservatively represents the test data. The stability relationship was developed using 24 combinations of stone size, bed slope, and highest stable discharge. Five verification tests, which included two field-scale structures, were

performed using larger stone, and these tests were accurately predicted by equation 1. Typical rock chute failure mechanisms were observed and described. The chutes typically failed just downstream of the horizontal crest on the sloping section by removing enough stone to expose the geofabric and/or filter material. The stability increased as the stone size increased and/or the slope decreased.

An empirical relationship was developed to predict the Manning roughness coefficient as a function of the median stone size and the bed slope. The Darcy-Weisbach friction factor was also predicted as a function of relative submergence. Once the roughness is determined, the flow depth in a rock chute can be calculated. Tests were performed with angular stone sizes ranging from 52 to 278 mm on slopes ranging from 2.5 to 33.3%. Flow depths were measured with piezometers placed in the bedding material. A procedure was developed to determine the effective top-of-riprap elevation, thereby determining the portion of the flow volume that is contained in the rock mantle.

The stability of rock chute outlets was examined in two separate flumes and two field-scale structures. Outlet tests were conducted on slopes ranging from 8 to 40% on angular riprap with a median stone size ranging from 52 to 278 mm. The tailwater downstream was regulated to examine tailwater to median stone size ratios of 3.0, 2.0, and the minimum resulting from the horizontal riprap section and downstream channel resistance. The downstream channel resistance was found to produce a minimum tailwater slightly less than $2D_{50}$. No notable movement of riprap was observed in the outlet section for any test. These test suggest that the riprap size required for stability on the slope will also be stable in the outlet reach. A horizontal outlet reach length of $15D_{50}$ is recommended downstream of the sloping chute. The elevation of the top of riprap at the exit of the outlet reach should be at or below the downstream channel bed elevation to prevent failure from downstream. The potential for bed degradation downstream of a chute should be considered when establishing the riprap elevation.

While not the focus of this study, numerous related design topics are discussed that can have a significant impact on rock chute design. These design relationships apply to angular riprap on slopes between 10 and 40% with a rock mantle thickness of $2D_{50}$. Appropriate engineering judgment should be applied when extending this design information beyond the data base from which it was developed.

References

- Abt, S.R., Khattak, M.S., Nelson, J.D., Ruff, J.F., Shaikh, A., Whittler, R.J., Lee, D.W., and Hinkle, N.E. 1987. Development of riprap design criteria by riprap testing in flumes: Phase 1, NUREG/CR-4651, U.S. Nuclear Regulatory Commission, Washington, D.C. 111 p.
- Abt, S.R. and T.L. Johnson. 1991. Riprap design for overtopping flow, *J. of Hydr. Engrg.*, Am. Soc. Of Civil Eng. 117(8):959-972.
- Anderson, A.G., A.S. Paintal, and J.T. Davenport. 1970. Tentative design procedure for riprap lined channels. Report No.108, Highway Research Board, National Academy of Sciences-National Academy of Engineering, Washington, D.C. 75 p.

American Society of Testing and Materials. 1996, *Annual Book of ASTM Standards*, Vol. 04.09, *Soil and Rock*, Standard test method for particle size analysis of natural and man-made riprap materials, D5519-94, pp. 331-336.

Frizell, K.H. and J.D. Ruff. 1995. Embankment overtopping protection - concrete blocks or riprap. Water Resources Conference, ASCE Proceedings, August 14-18, San Antonio, TX, pp. 1021-1025.

Isbash, S. 1936. Construction of dams by depositing rock in running water. Communication No. 3, Second Congress on Large Dams, Washington, D.C., pp. 123-136.

Maynard, S.T. 1988. Stable riprap size for open channel flows, U.S. Army Corps of Eng. Waterways Exp. Sta., Tech. Report HL-88-4. 122 p.

Maynard, S. T. 1992. Steep stream riprap design, Streams above the line: channel morphology and flood control. Proceedings of Corps of Engineers Workshop on Steep Streams, 27-29 October, Seattle, Washington, Miscellaneous Paper HL-94-4, Waterways Experiment Station, Vicksburg, MS. 9 p.

Rice, C.E., K.C. Kadavy, and K.M. Robinson. 1997. Roughness of loose rock riprap on steep slopes. *J. of Hydr. Engrg.*, Am. Soc. Of Civil Eng. (In press)

Rice, C.E., K.M. Robinson, and K.C. Kadavy. 1996. Rock riprap for grade control. Proceedings of ASCE North American Water and Environment Congress, Anaheim, CA. June 22-28, 1996. CD-ROM.

Robinson, K.M., C.E. Rice, and K.C. Kadavy. 1995. Stability of rock chutes. Water Resources Conference, ASCE Proceedings, August 14-18, San Antonio, TX, pp. 1476-1480.

Robinson, K.M. C.E. Rice, and K.C. Kadavy. 1997. Rock chutes for grade control. Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision, Edited by Sam S.Y. Wang, Eddy J. Langendoen, and F. Douglas Shields, Jr. pp 211-216, May 19-23, The University of Mississippi.

Stephenson, D. 1979. Rockfill in hydraulic engineering. Elsevier, Amsterdam, The Netherlands.

Whittler, R.J. and S.R. Abt. 1990. The influence of uniformity on riprap stability. Proceedings of the Am. Soc. Of Civil Engrs. National Conference on Hydraulic Engineering, July 30-August 3, 1990, San Diego, CA. pp. 251-256.

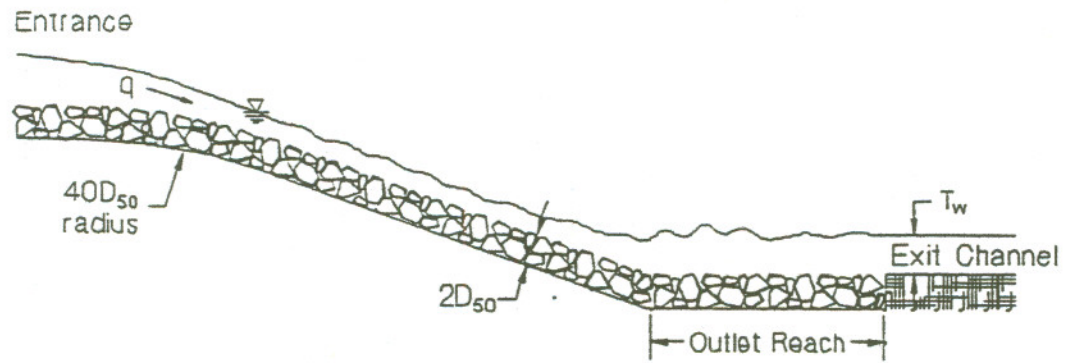


Figure 1. Typical rock chute profile

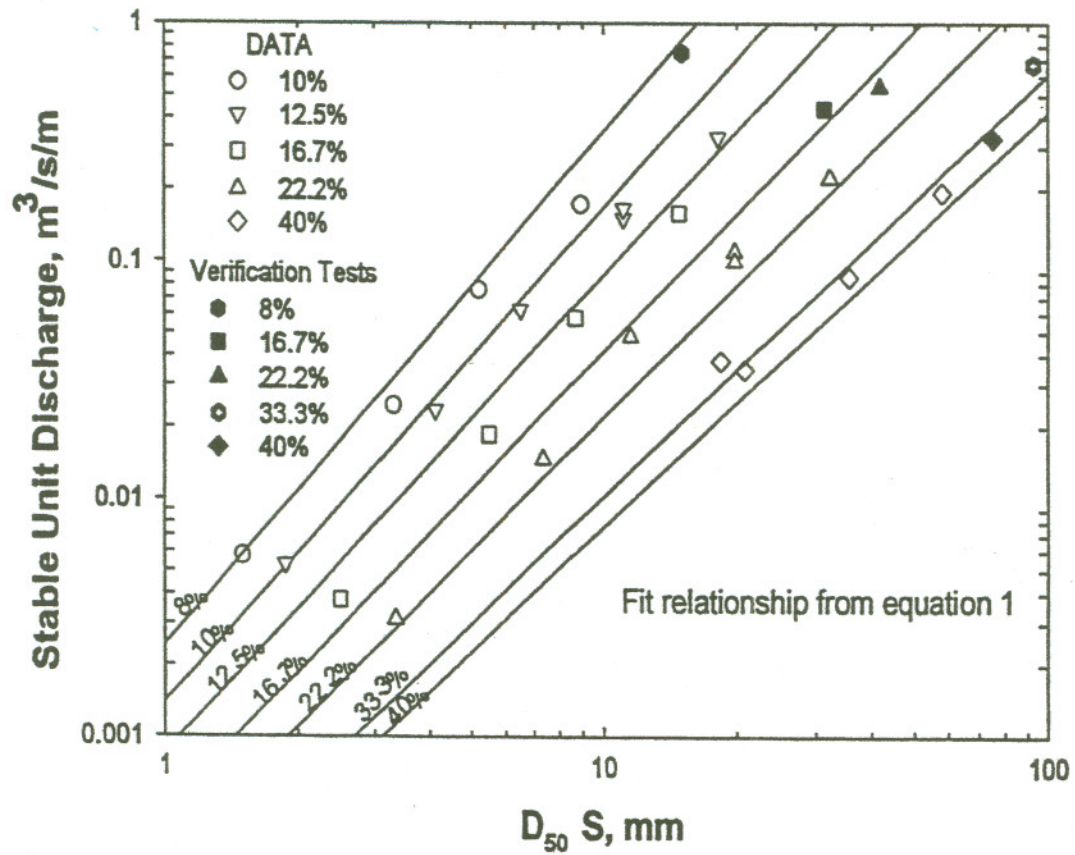


Figure 2. Rock chute slope stability data

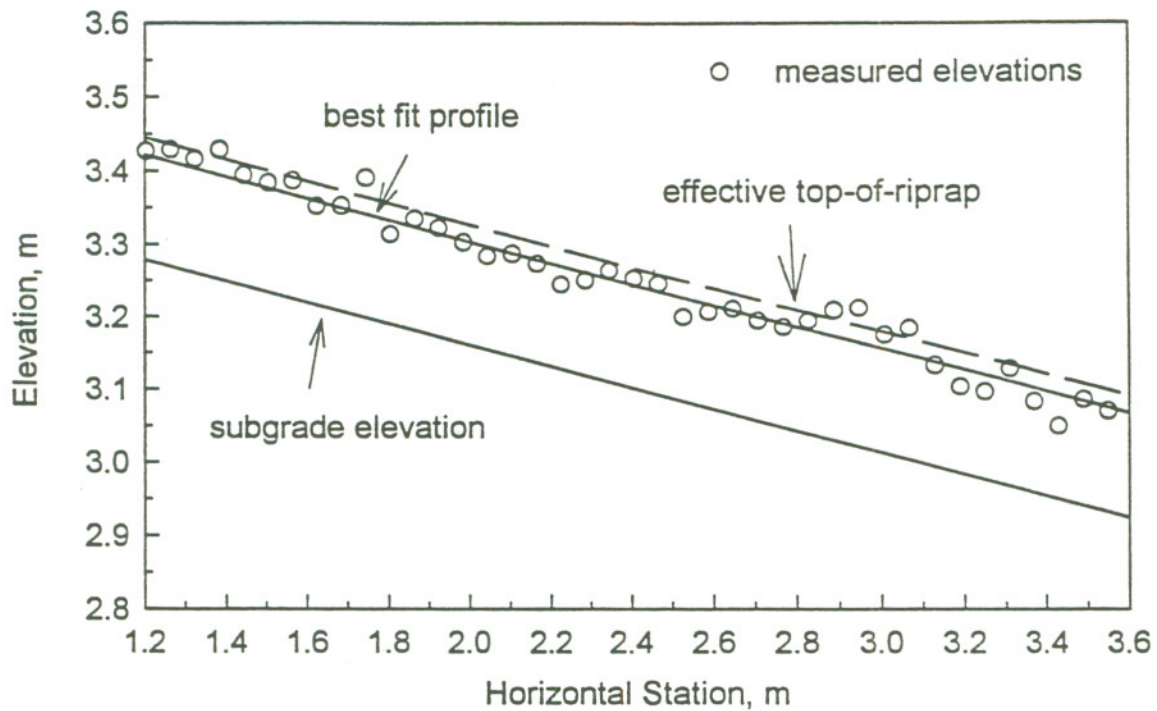


Figure 3. Top-of-riprap elevation

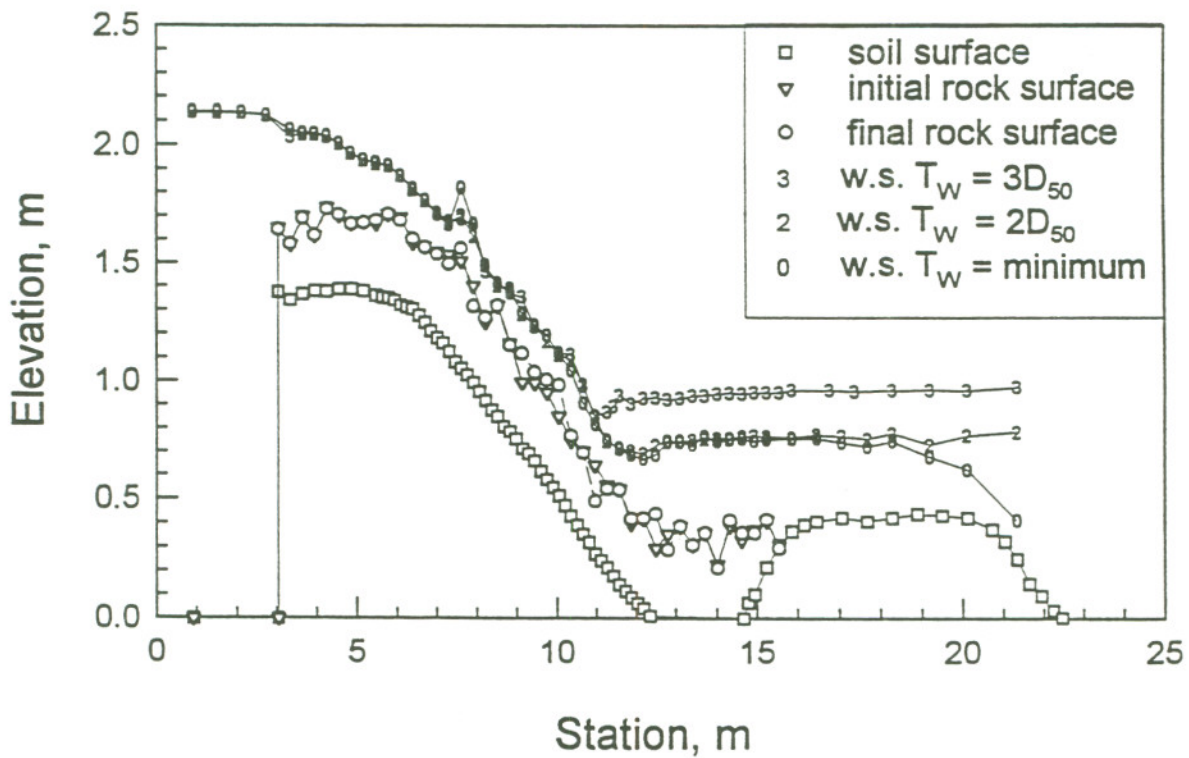


Figure 4. Bed and water surface profiles, 22.2% slope, $D_{50} = 188 \text{ mm}$, and $q = 0.351 \text{ m}^3/\text{s/m}$